Point-Cloud based Diffusion Model on Hadronic Showers

Erik Buhmann[1], Thorsten Buss[1], Frank Gaede[2], Gregor Kasieczka[1], Anatolii Korol[2], William Korcari[1], Katja Krüger[2], Peter McKeown[2], **Martina Mozzanica[1]***, Lorenzo Valente[1]

[1] University of Hamburg, UHH
[2] Deutsches Elektronen-Synchrotron, DESY

*martina.mozzanica@uni-hamburg.de

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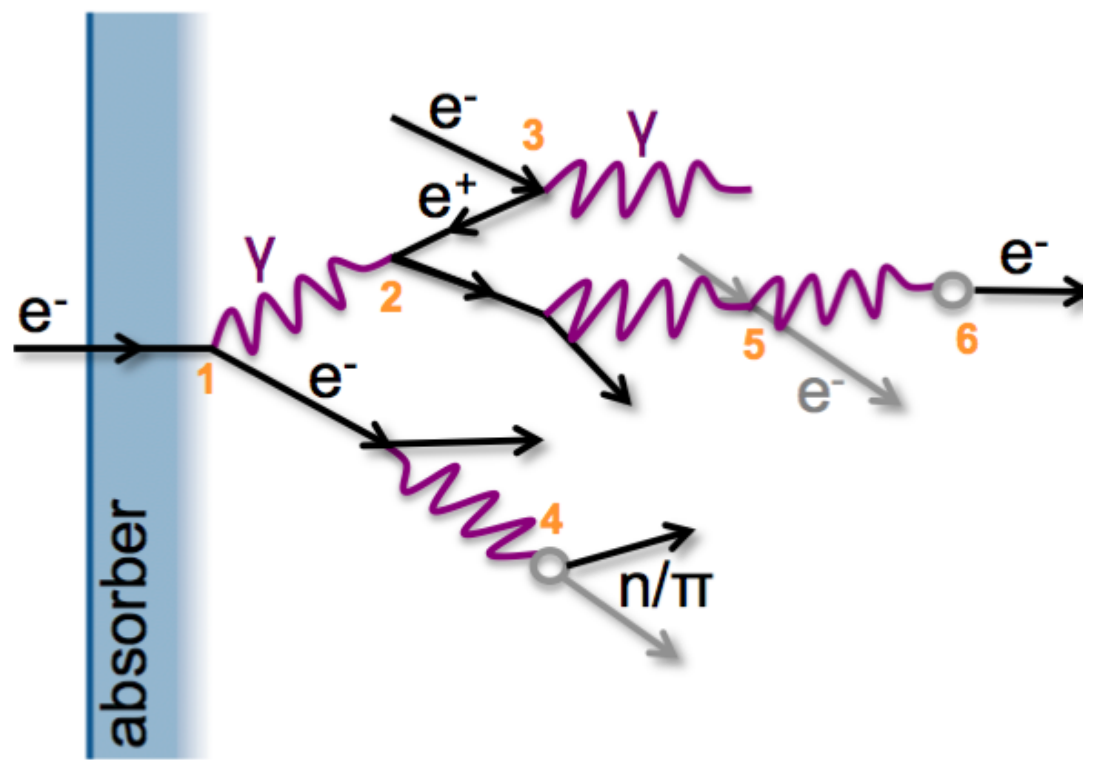
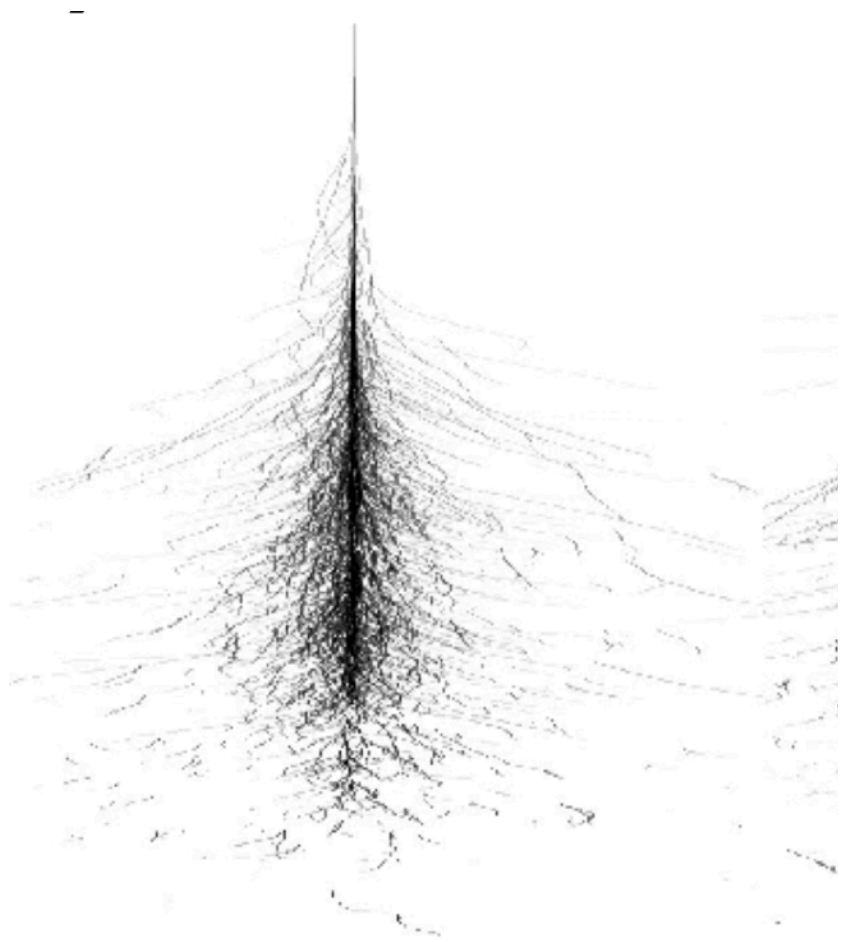
Generative Model for EM and Hadronic Showers

- **CaloClouds II** [1]: Fast & accurate point clouds based generative model —> applied **only to EM showers**

[1] CaloClouds II: Ultra-Fast Geometry-Independent Highly-Granular Calorimeter Simulation
E. Buhmann et al: arxiv: 2309.05704





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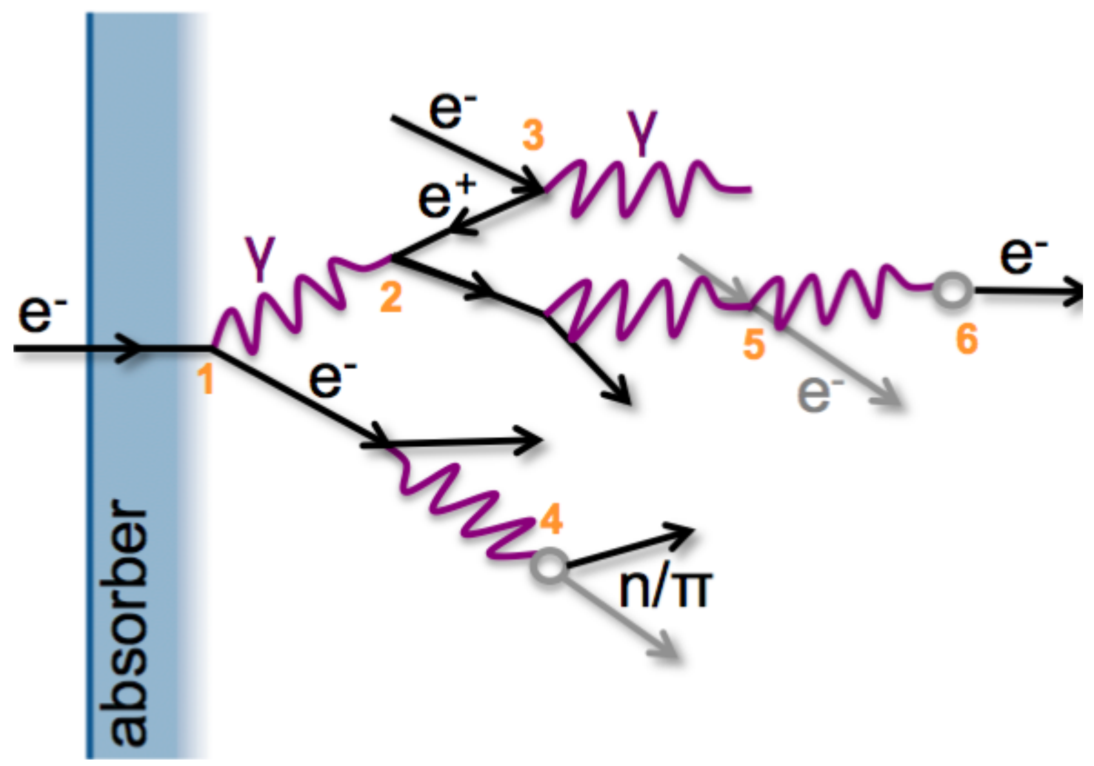

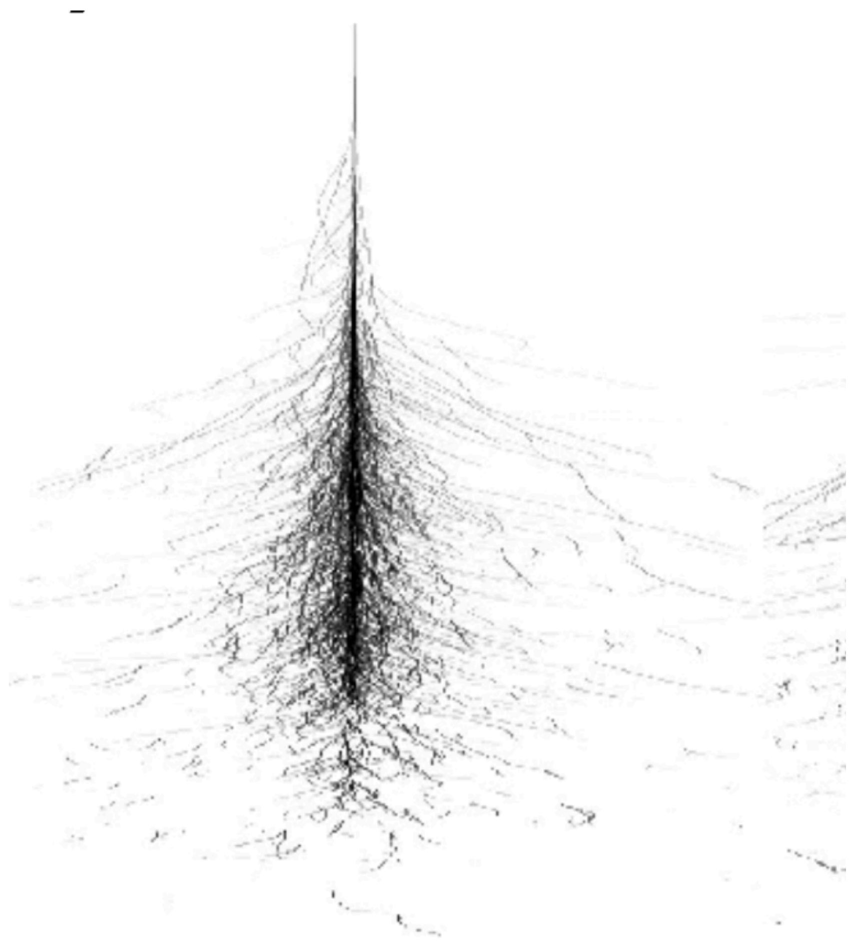

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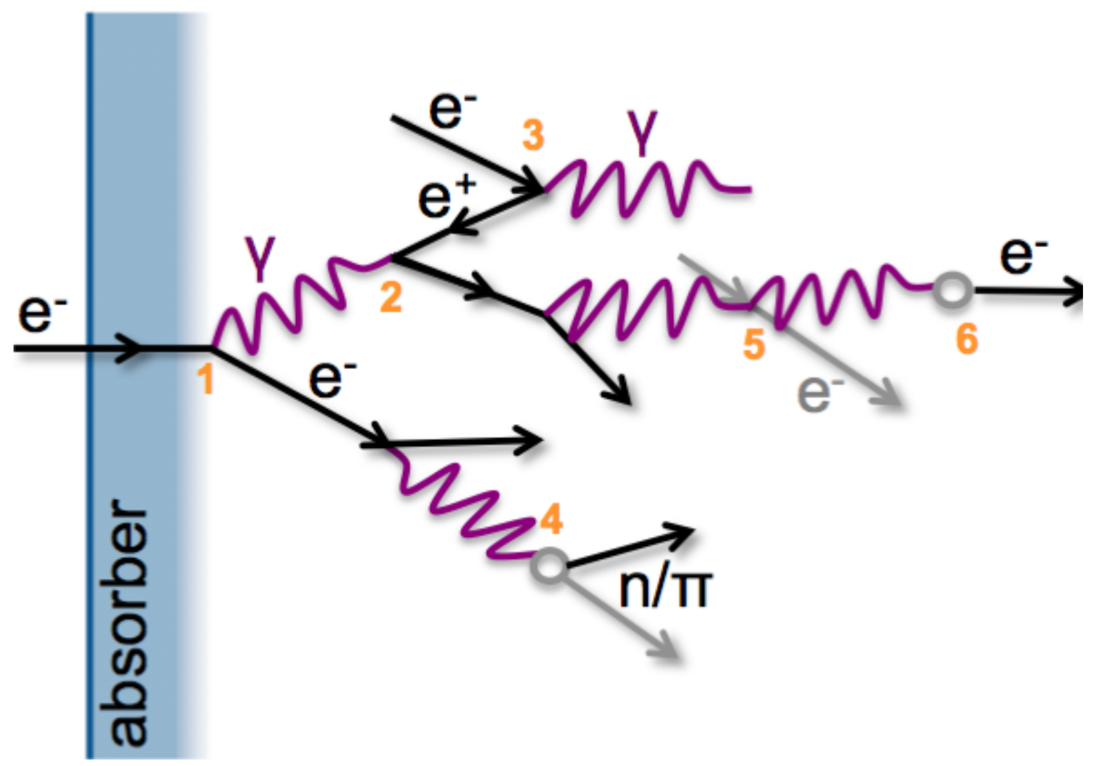
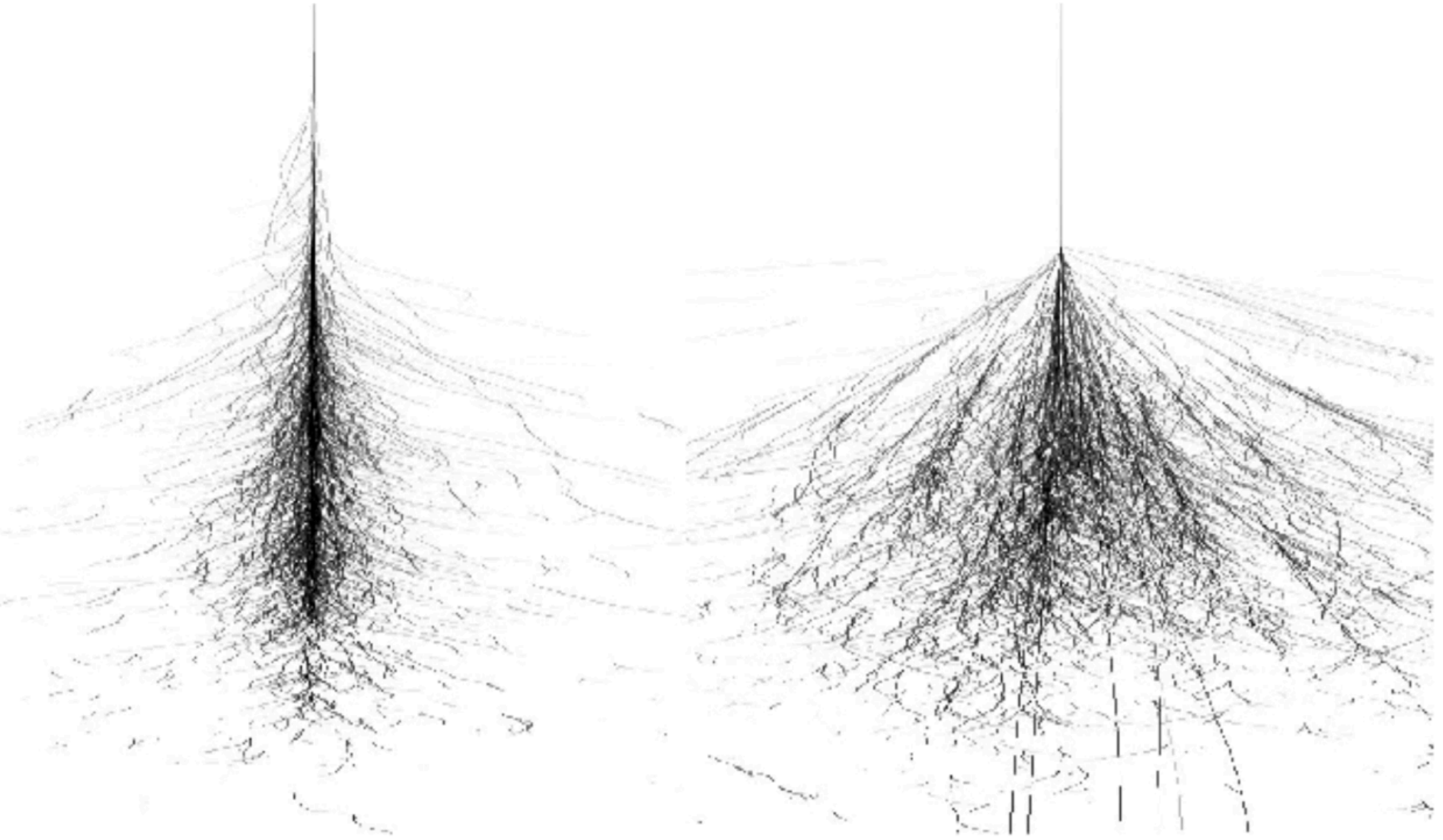
Dealing with 10-90 GeV π^+ showers
two components: hadronic and electromagnetic

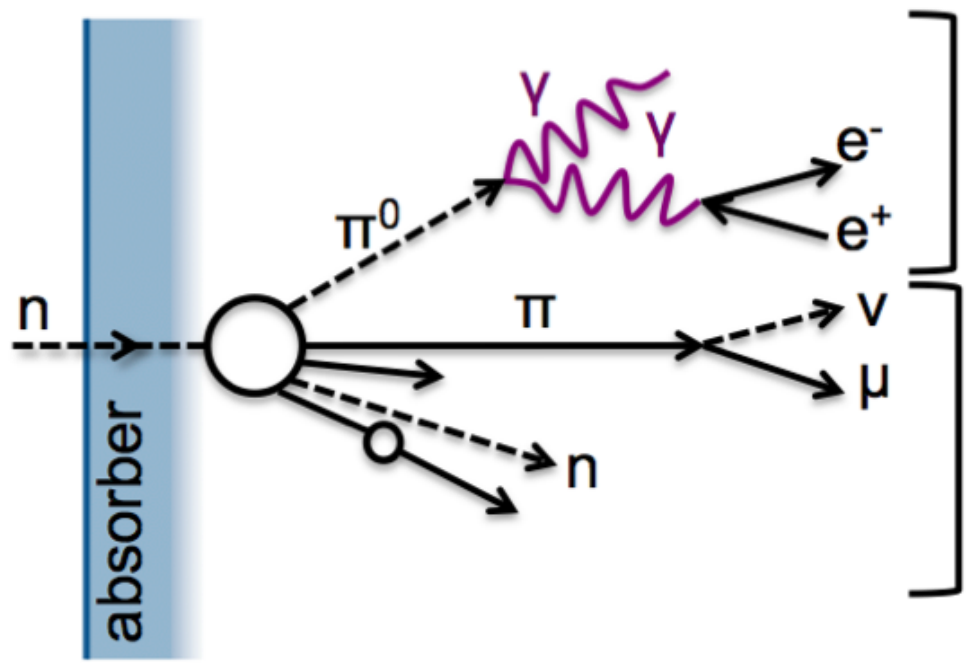
Hadron showers have **much larger:**

- **spatial extension** -> larger interaction length than radiation length
- **lateral dispersion** -> large transverse energy transfers in nuclear reactions





Gamma shower   Hadronic shower



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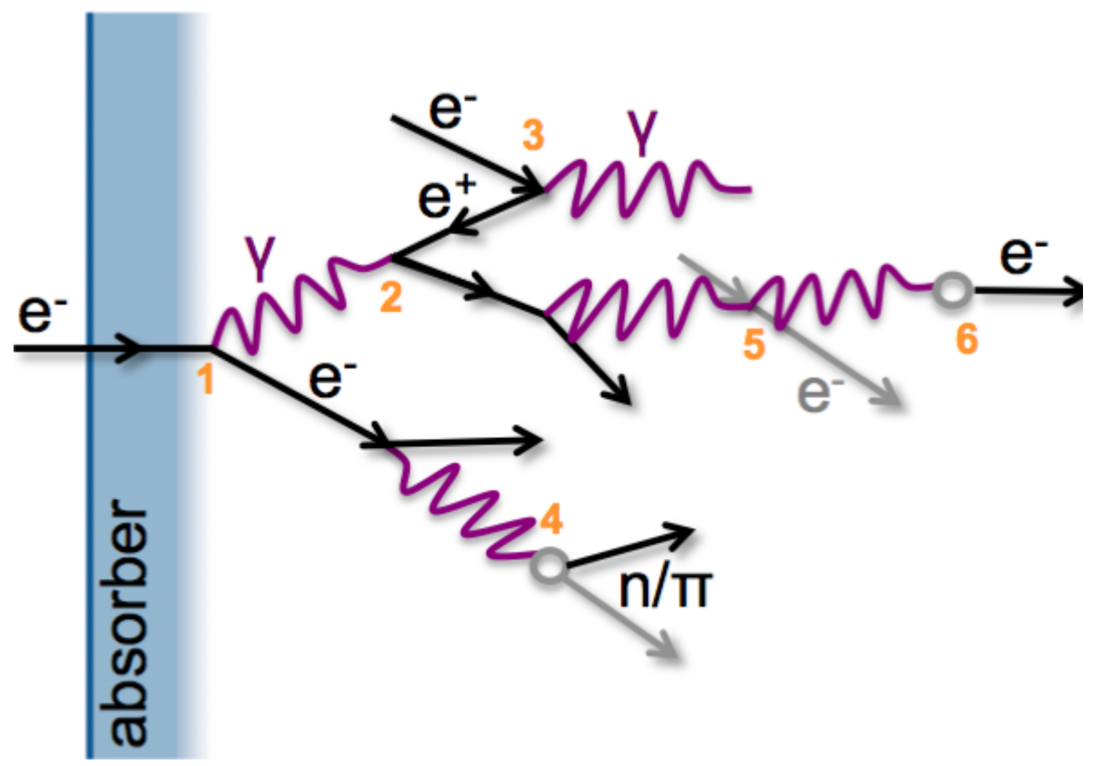

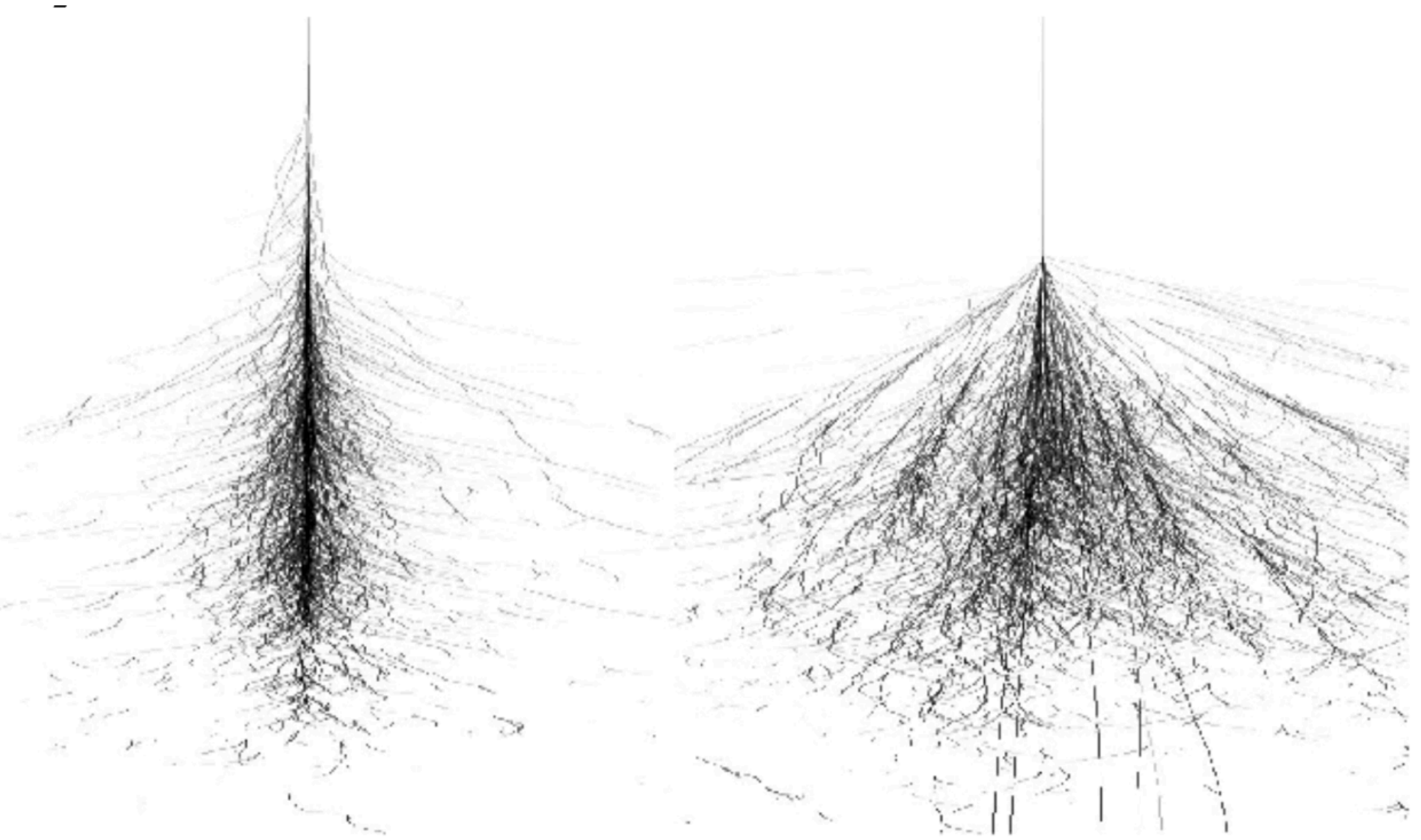
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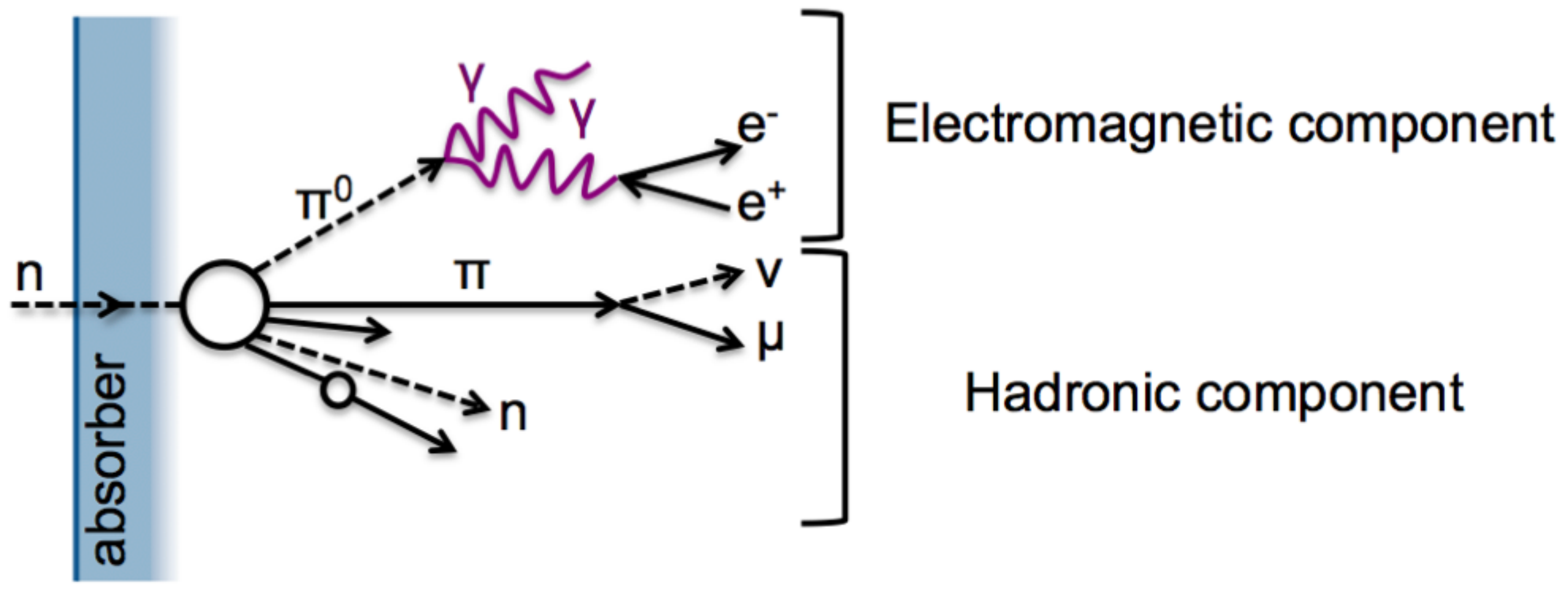
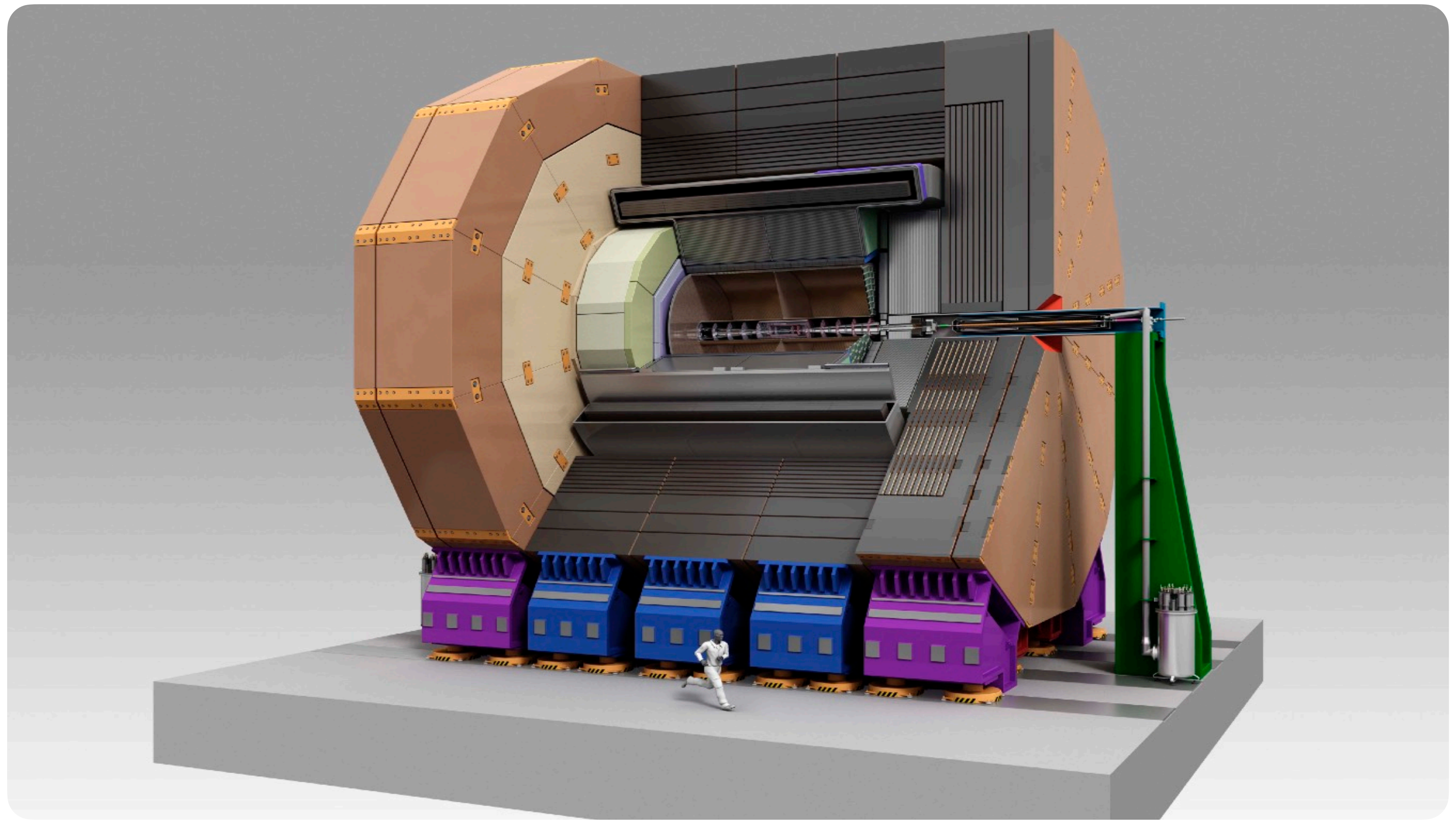


Hadronic cascades are much more complex than em cascades!

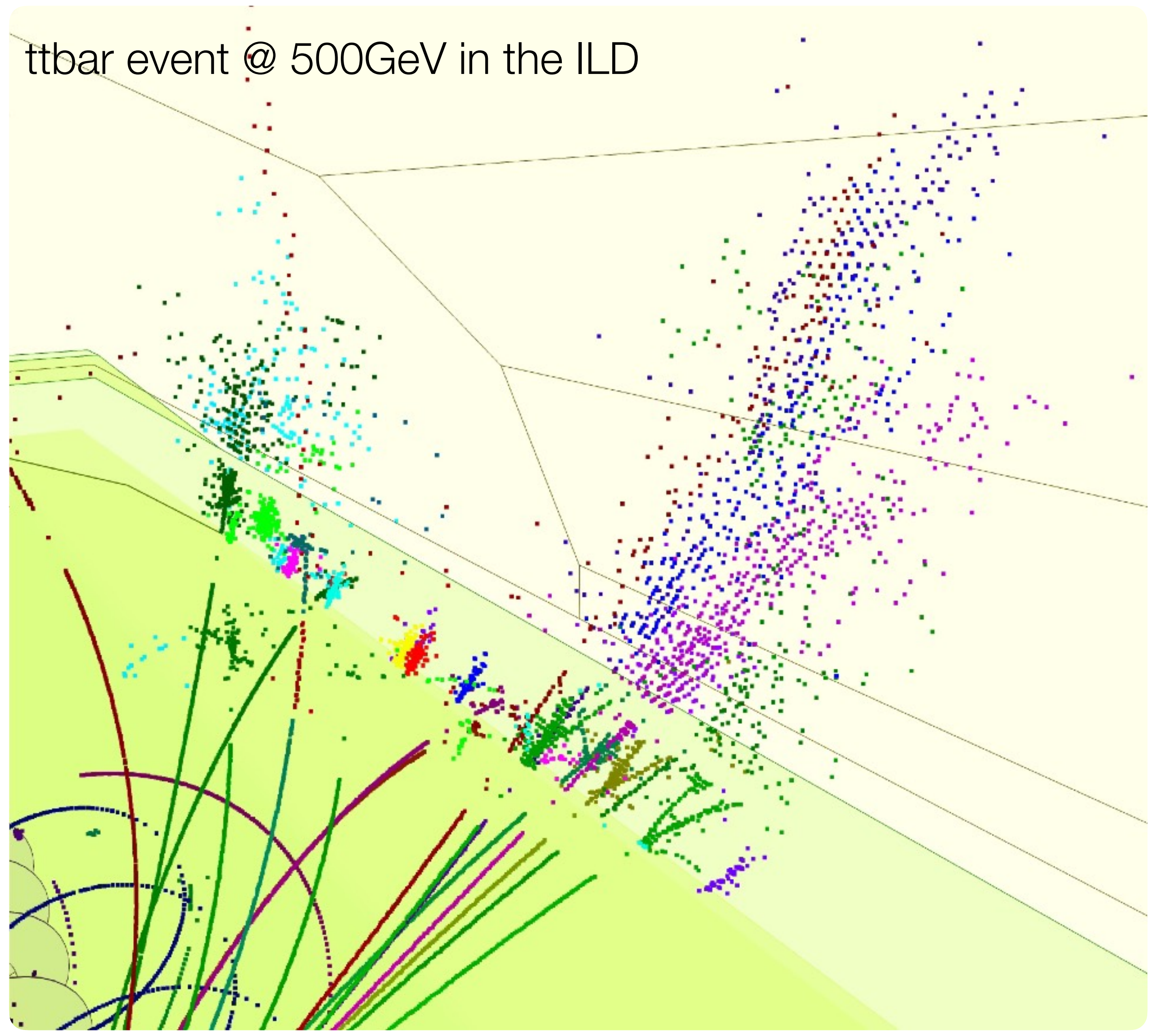
ILD calorimeter

- International Large Detector (ILD) concept for the International Linear Collider (ILC)

- High-Granularity calorimeters:
  - ECAL: Si-W - 5mm x 5mm - 30 layers
  - HCAL: Sci-Fe - 30mm x 30mm - 48 layers



High granularity → Need for high fidelity simulation



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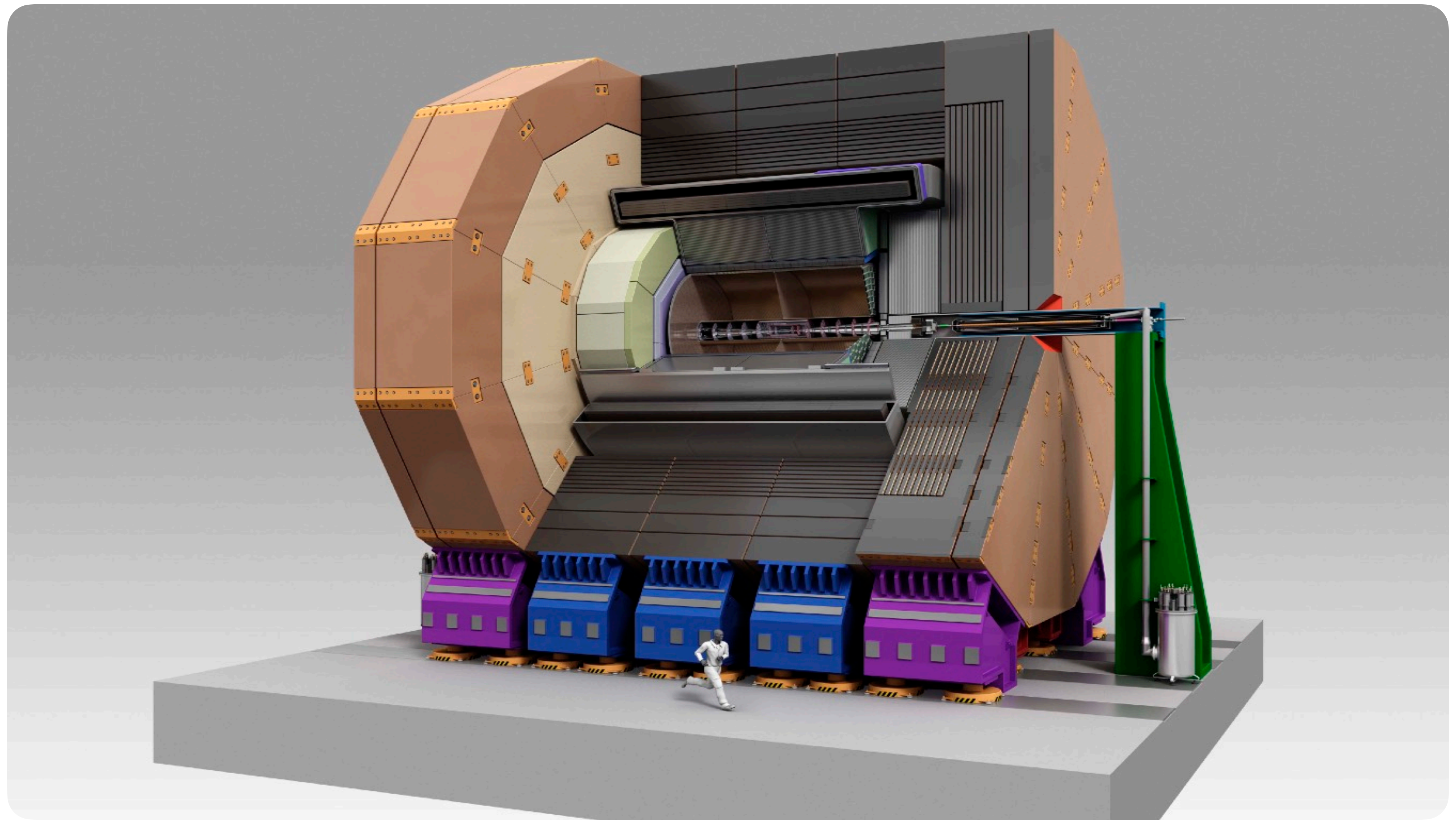

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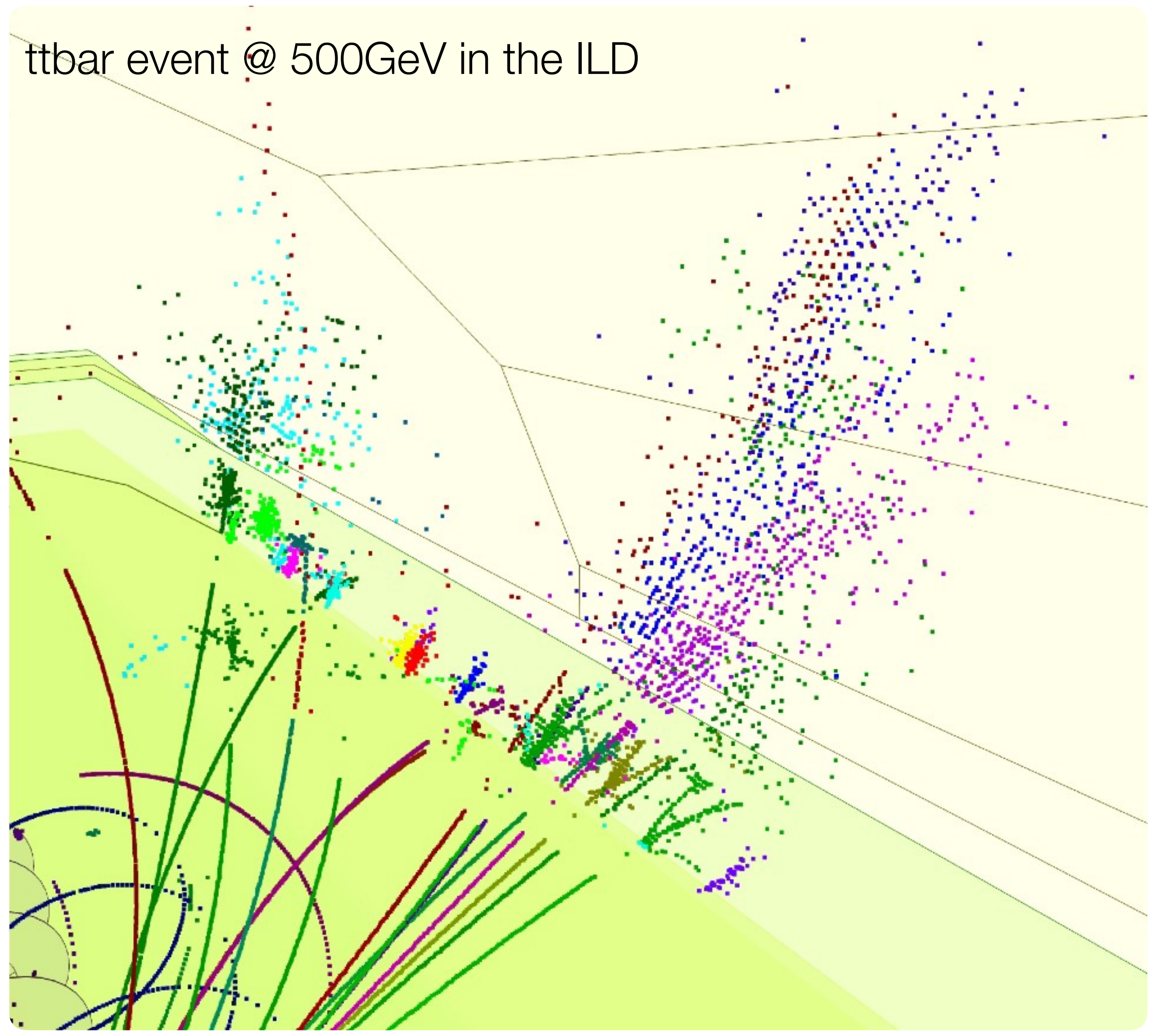
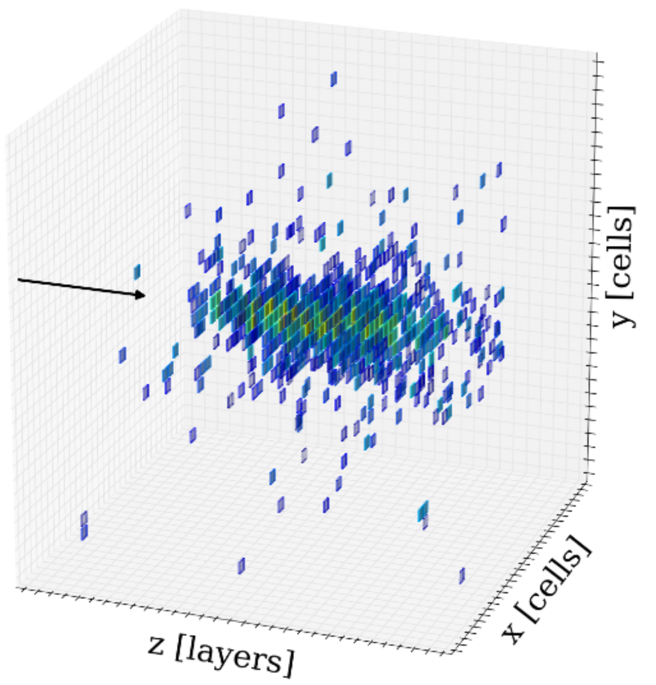
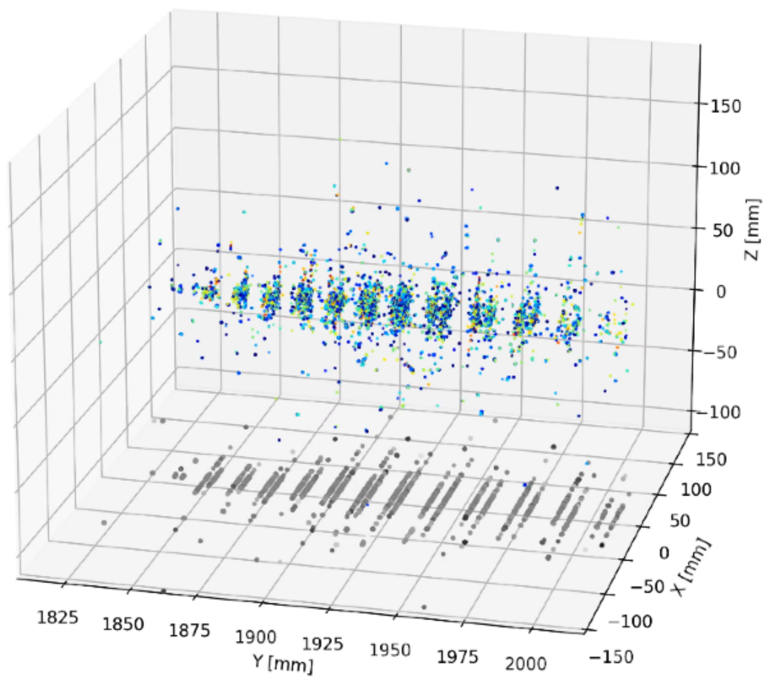


EM shower as 3D image



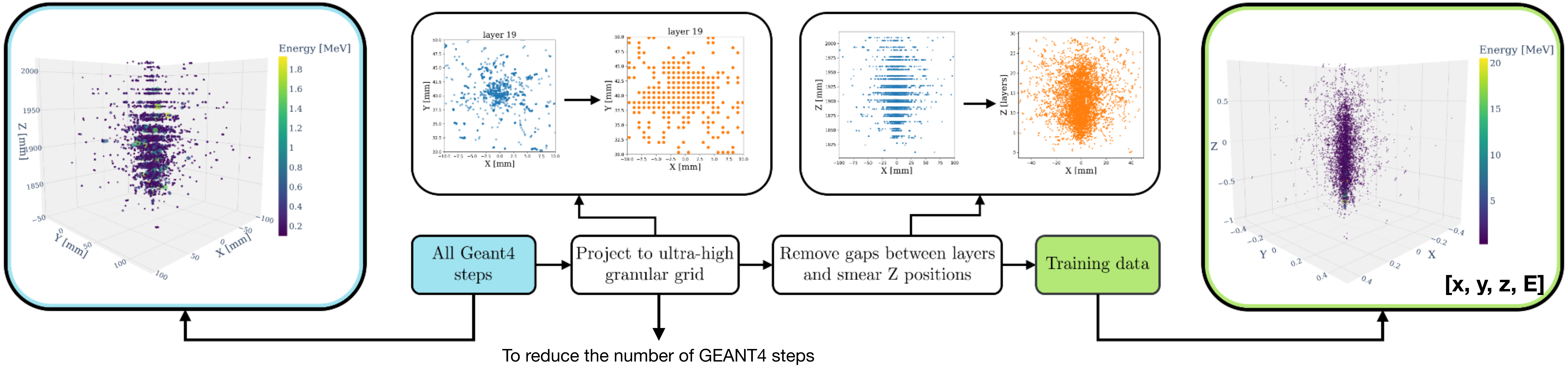
EM shower as point cloud



Generative models for calorimeter showers usually applied to fixed geometries -> more economically represented as **point clouds**

Multiple points per cell & cell-geometry independence

Showers as Point Clouds and Preprocessing



Point clouds of clustered Geant4 steps:

- higher granularity than cell hits
- ~3x fewer points than full Geant4 steps for hadronic showers

	Photon	**Pion+**	Note
Shower type	Only EM	EM + Hadronic	
All GEANT4 steps	40 000	40 000	Initial input of GEANT4
High granular cell size	0.3 cm	2.5 cm	Defines the granularity
Clustered GEANT4 steps	6 000	**13 000**	Input/Output of CaloClouds
Hits in calorimeter	1 500	**4 000**	Calculation of physics observables

Score-based continuous-time diffusion [2]

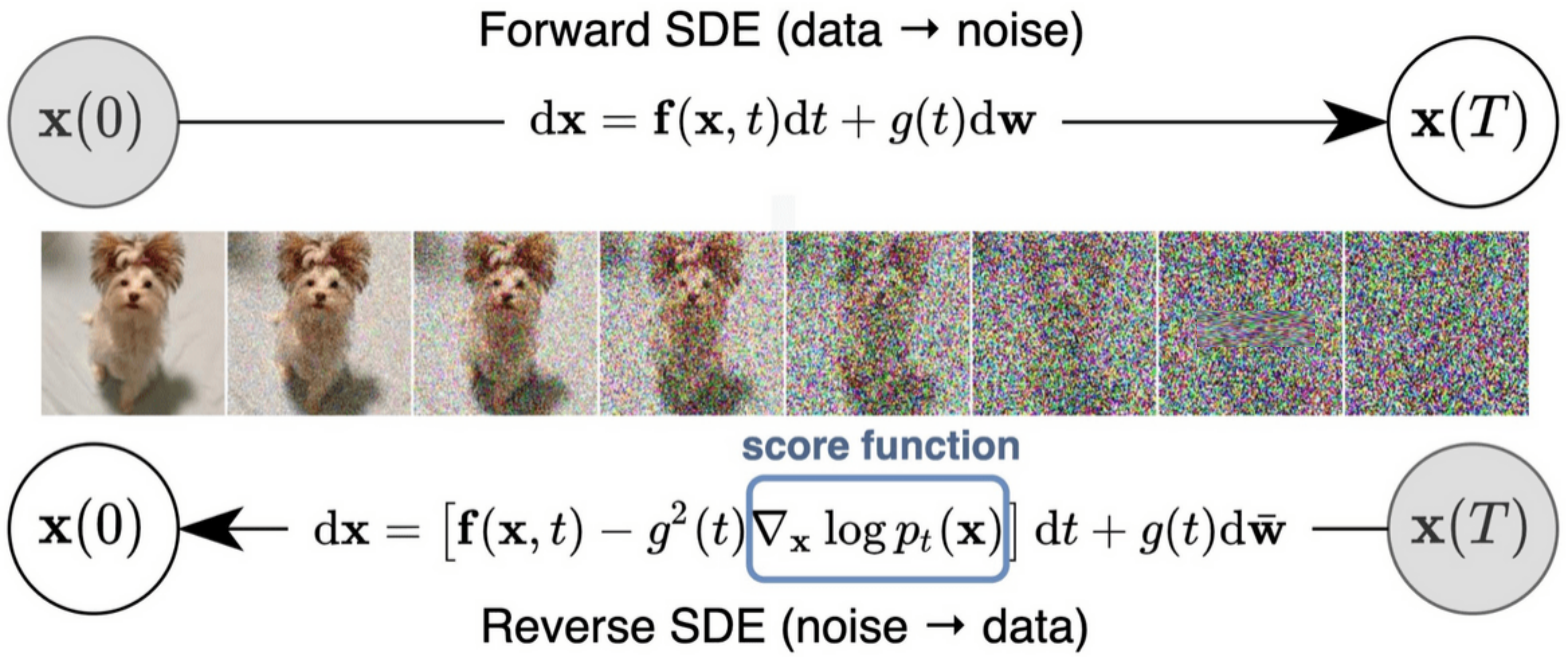
Continuous Time:

- continuum of distributions that evolve over time

- This process is modeled by a prescribed stochastic differential equation (SDE)

Scored-based:

- Score-matching: process of modelling the gradient of the log probability density function (=score function)
- Langevin dynamics is an iterative process that can draw samples from a distribution using only its score function



To compute the reverse SDE, we need to estimate the score function:

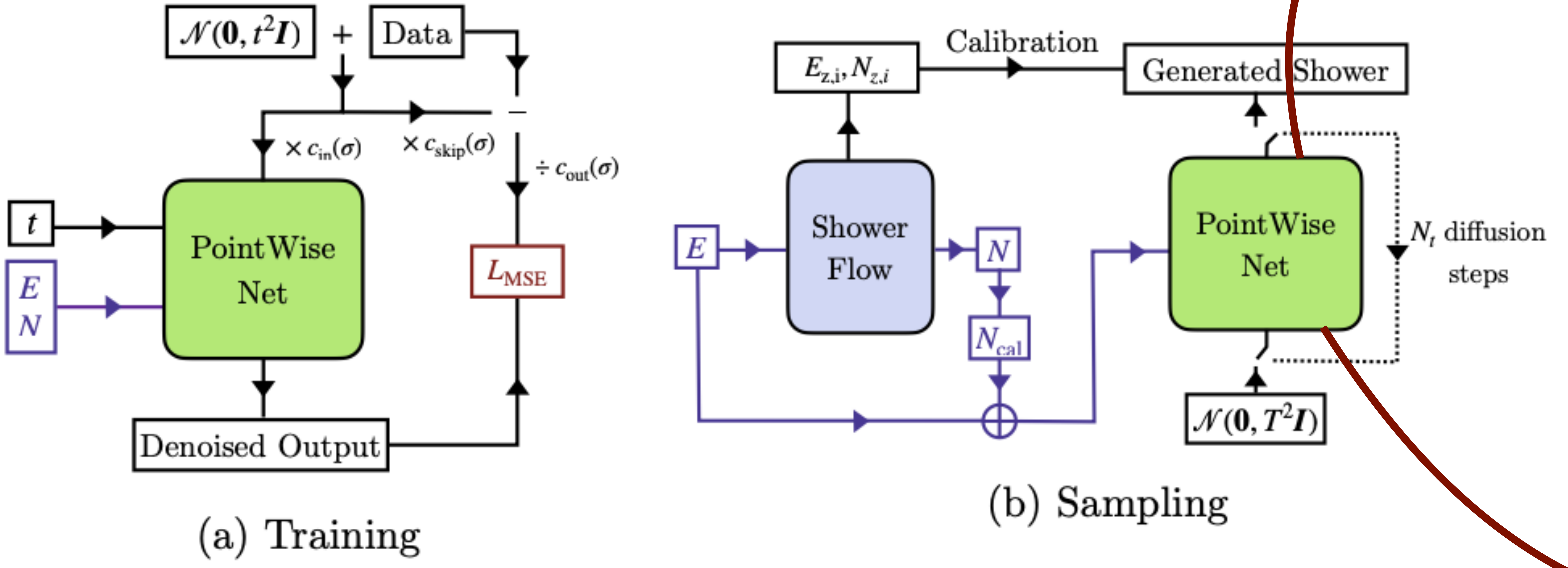
$$\mathbb{E}_{t \in \mathcal{U}(0,T)} \mathbb{E}_{p_t(\mathbf{x})} \left[\lambda(t) \|\nabla_{\mathbf{x}} \log p_t(\mathbf{x}) - \mathbf{s}_\theta(\mathbf{x}, t)\|_2^2\right]$$

↑ Scored based model

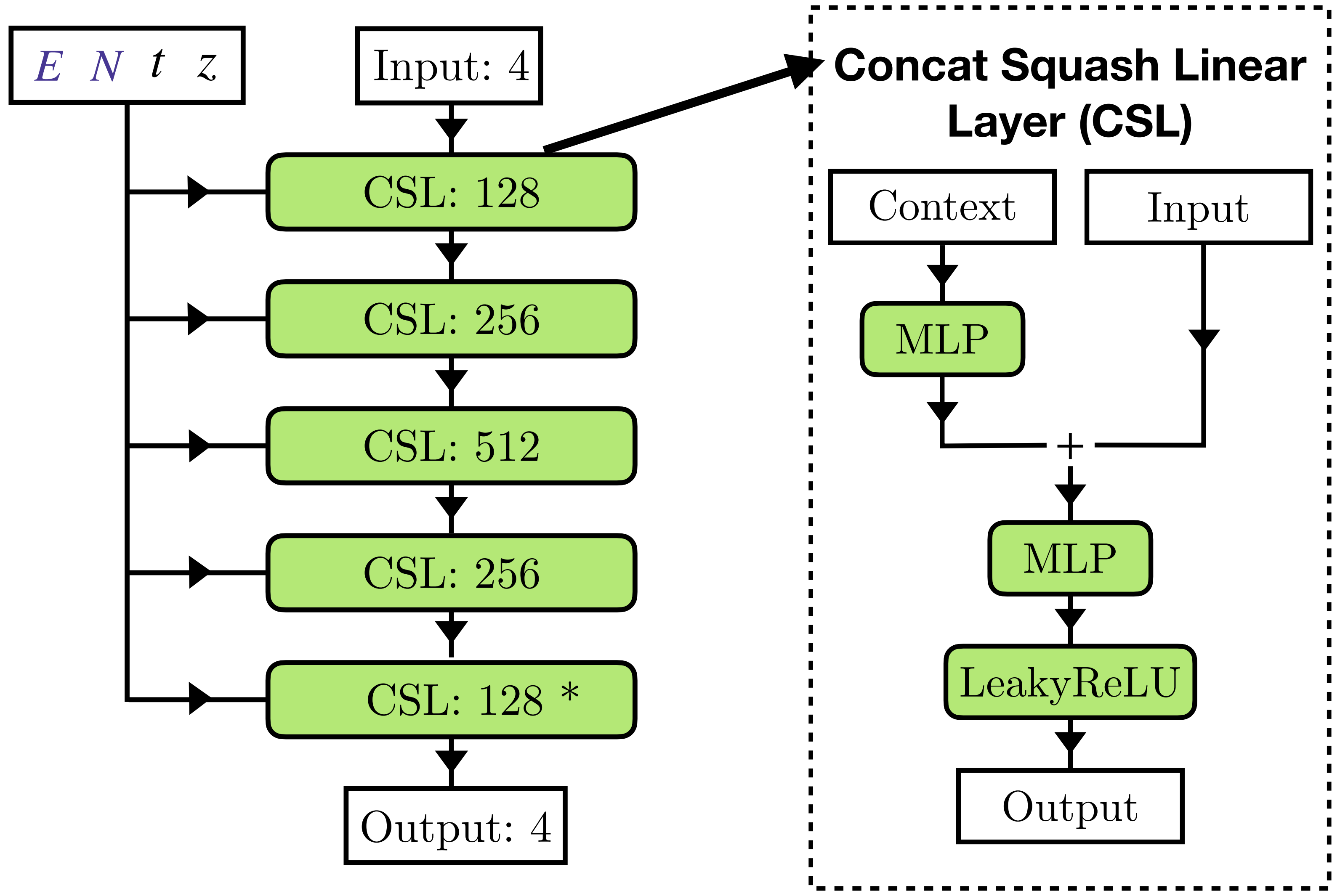
[2] Score-based Continuous-time Discrete Diffusion Models
Haoran Sun et al: arxiv: 2211.16750

Calo Clouds II [3] architecture based on [4]

- <u>input:</u> 4d point cloud
- <u>conditioning</u>: incident energy (E) and number of points (N)



Diffusion Architecture based on Concat Squash Linear Layers (CSL)



Point wise net = each point is independent from the others

[1] CaloClouds II: Ultra-Fast Geometry-Independent Highly-Granular Calorimeter Simulation
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[4] Elucidating the Design Space of Diffusion-Based Generative Models
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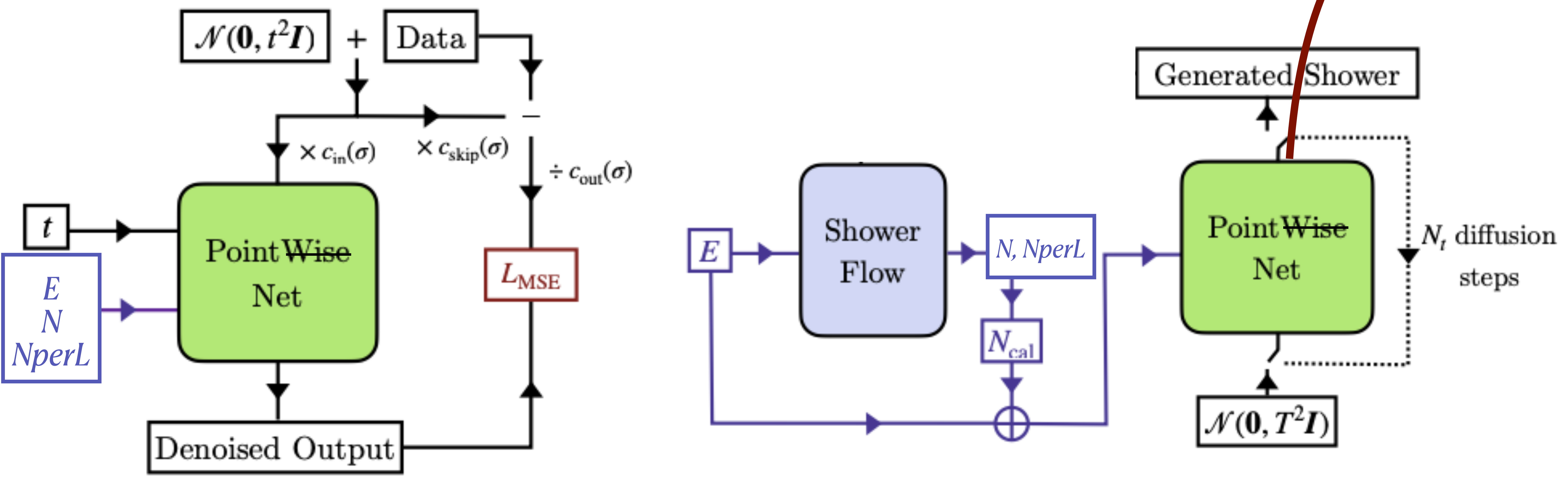

(a) Training

(b) Sampling

Transformer-like layers

No longer Point wise!

points know about the other points in the shower

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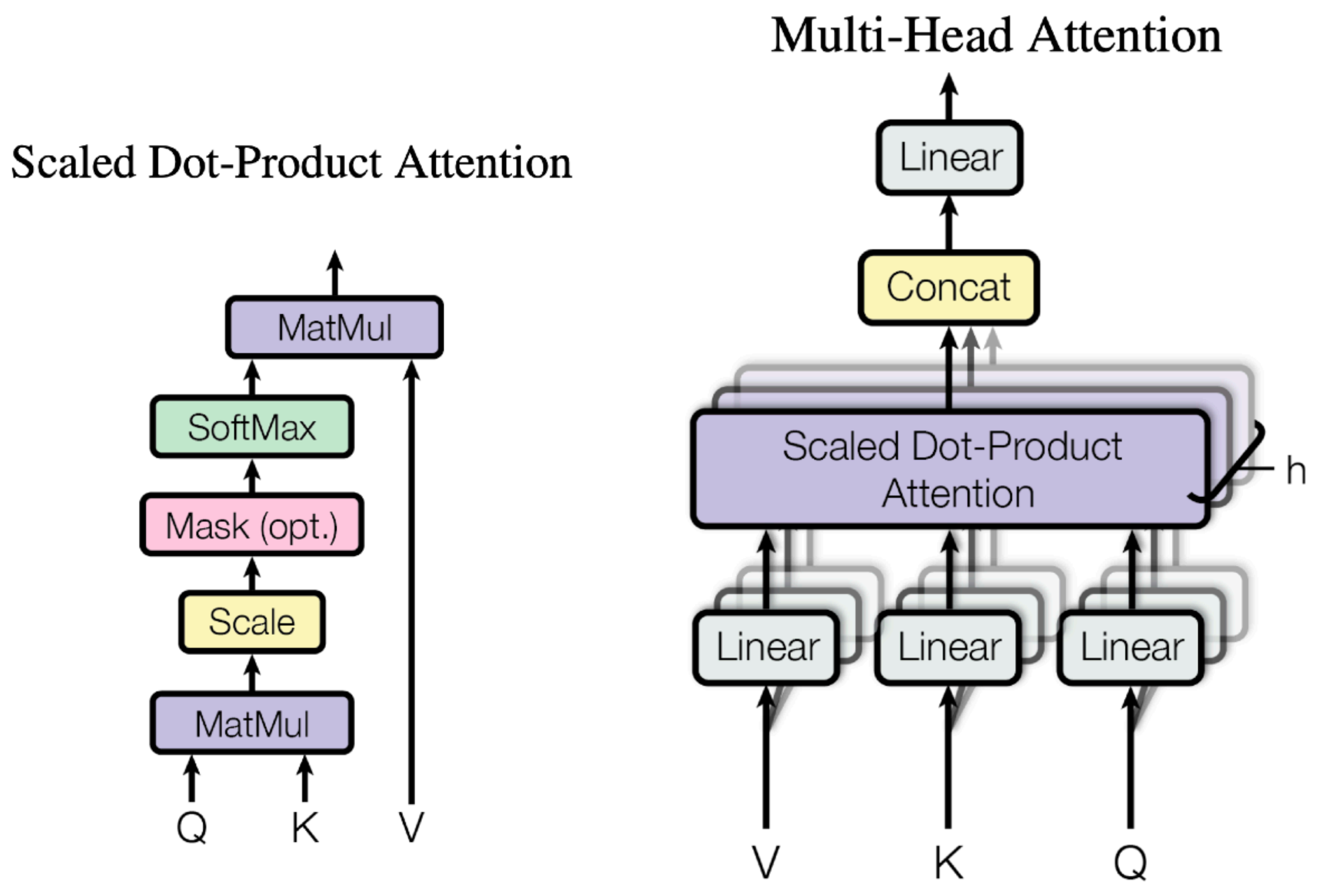
Attention Mechanism in the CaloClouds II architecture

Attention mechanisms [6] allows modelling of dependencies without regard to their distance in the input or output sequences

Self Attention based architecture



[6] Attention is all you need
A.Vaswani et al: arXiv: 1706.03762

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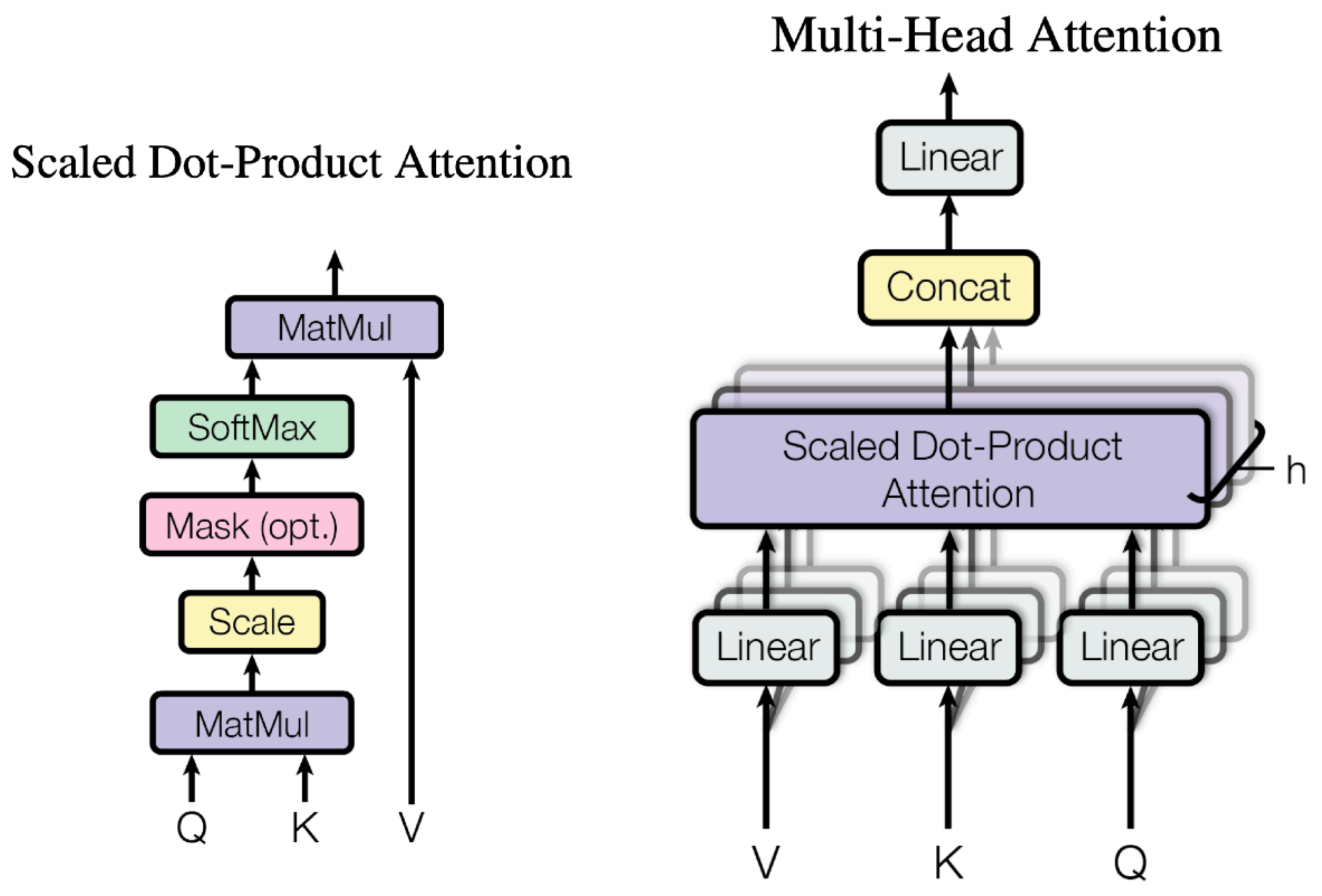
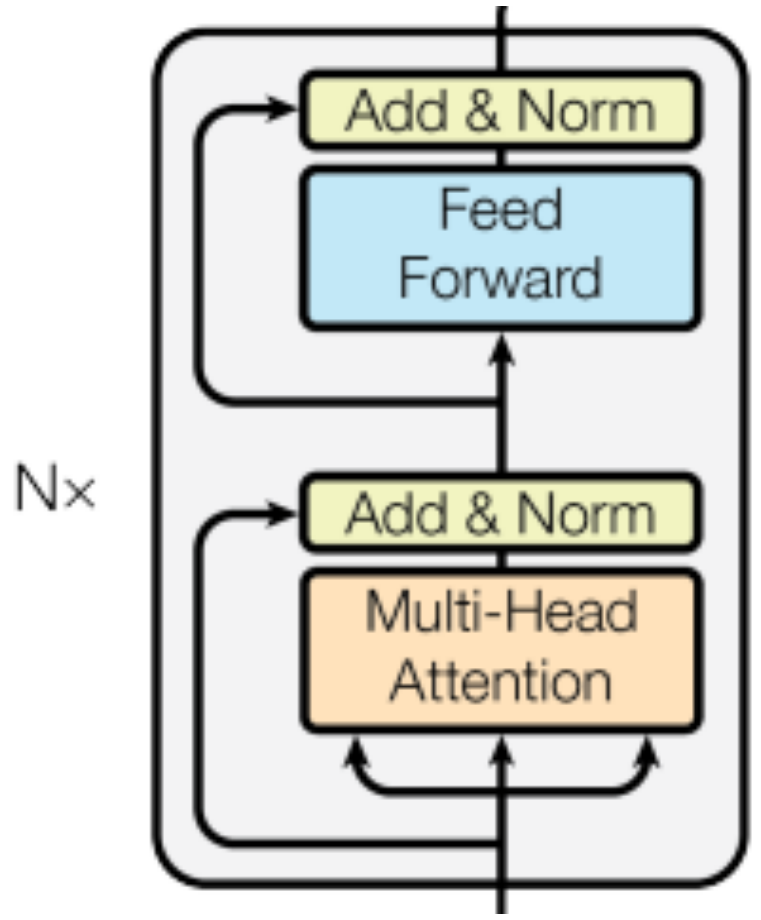


Transformer encoder [6]



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N heads = 4

dim_feedforward = 512

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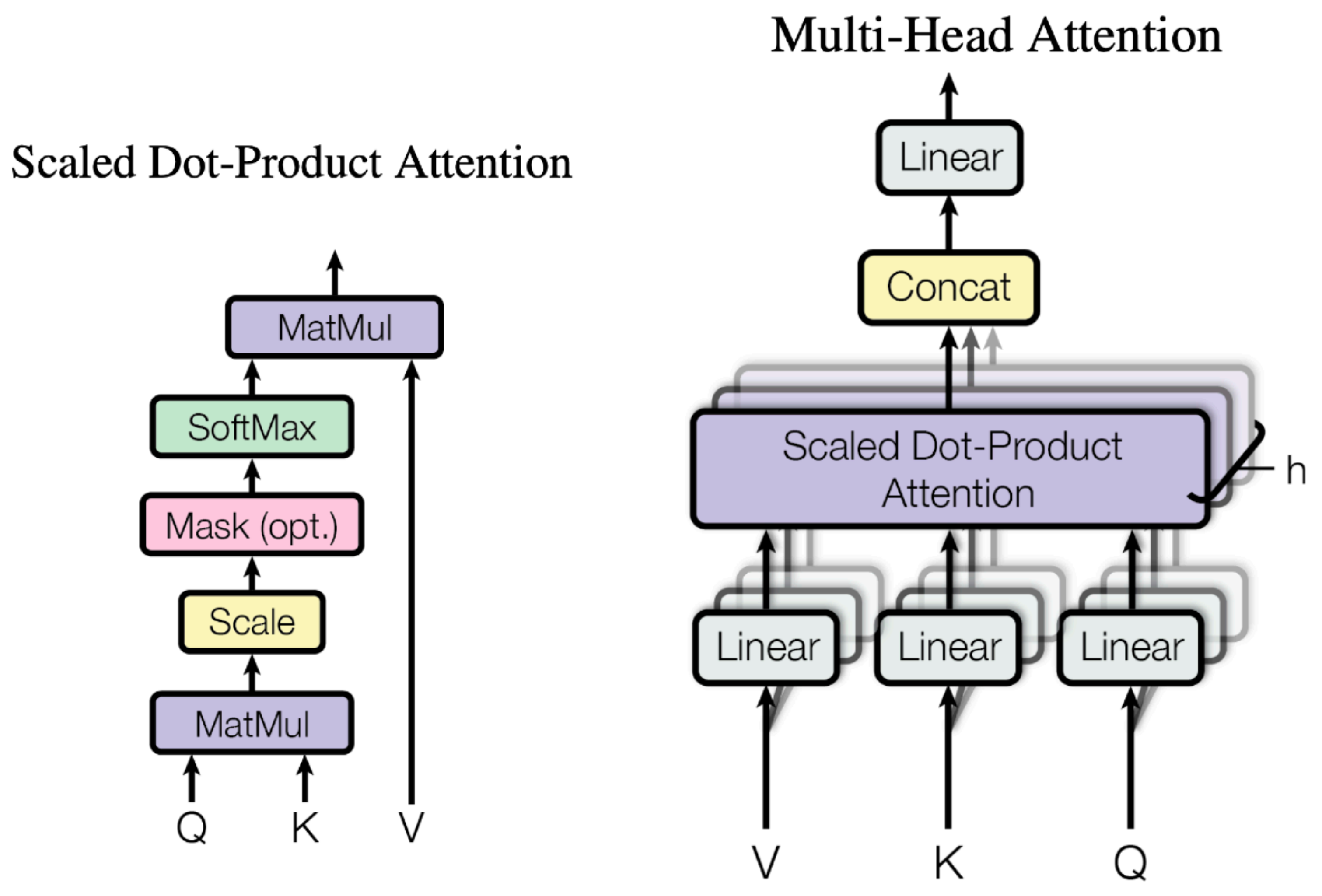

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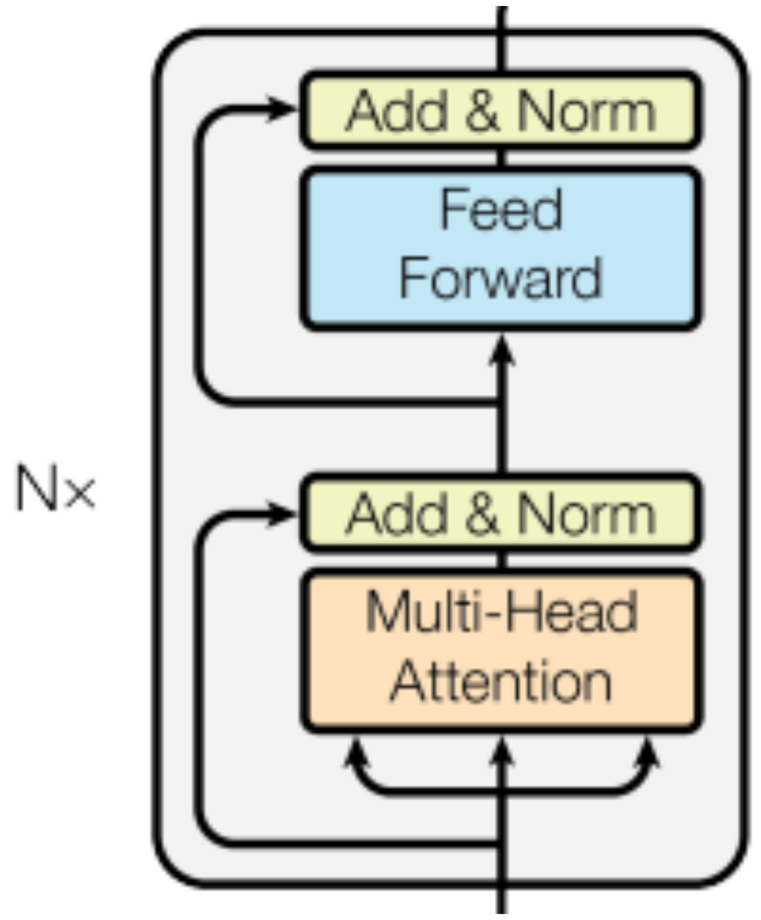

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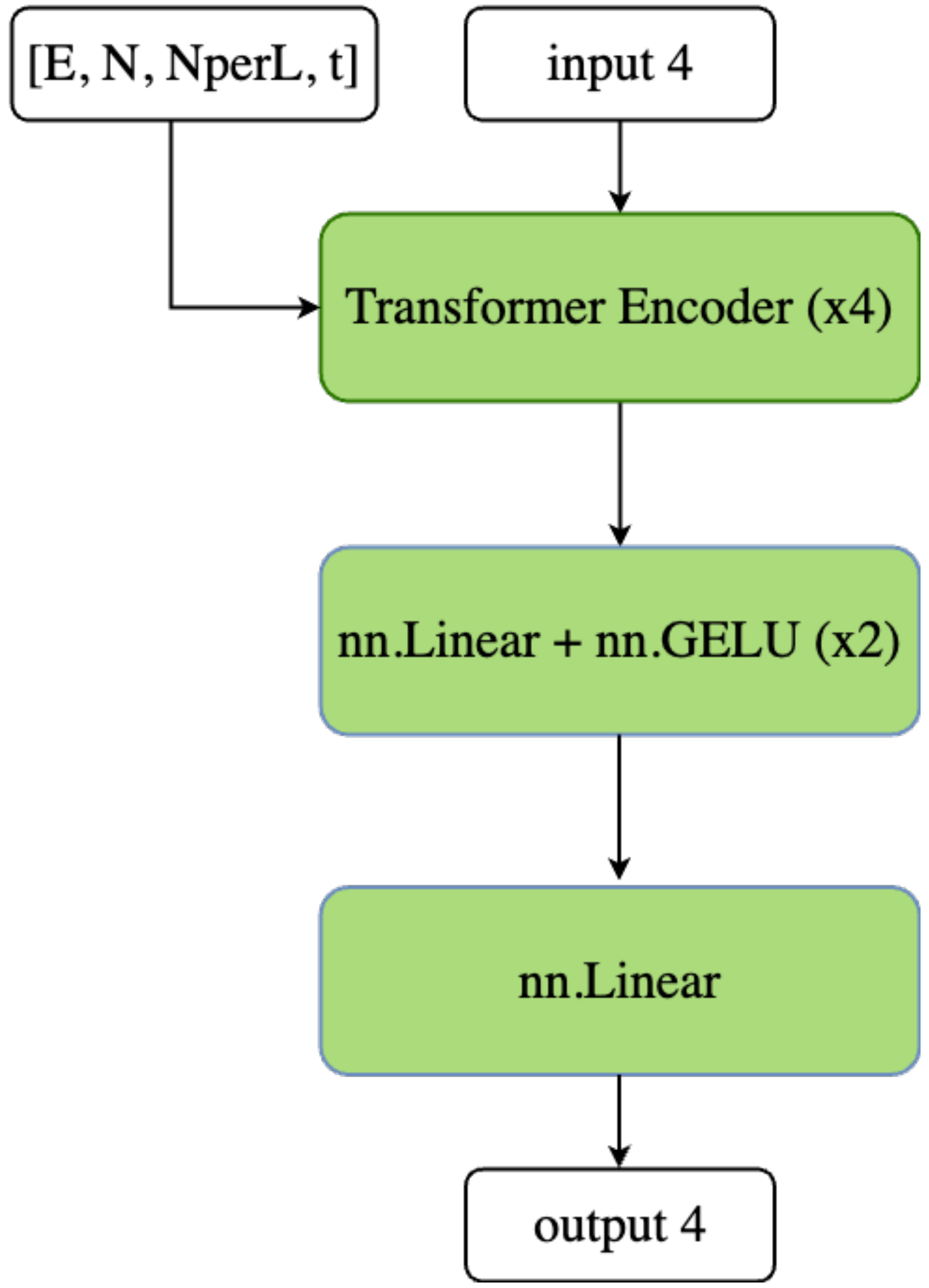
Diffusion Layers



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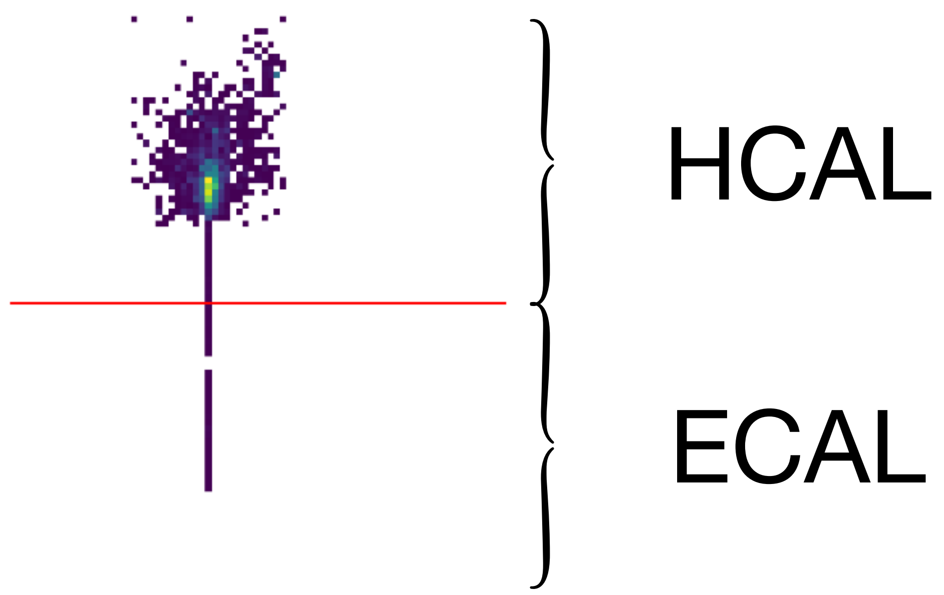
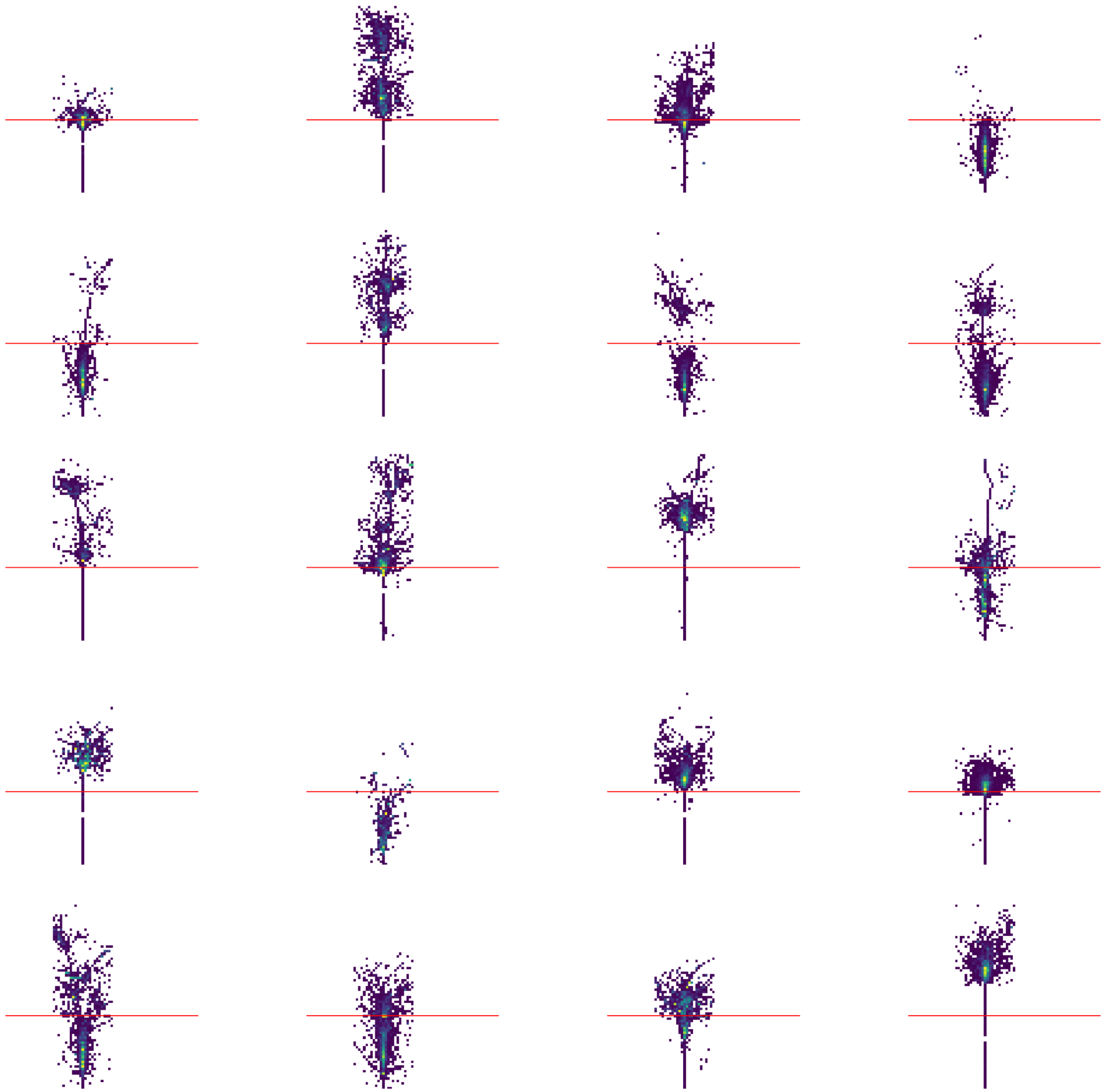
Results

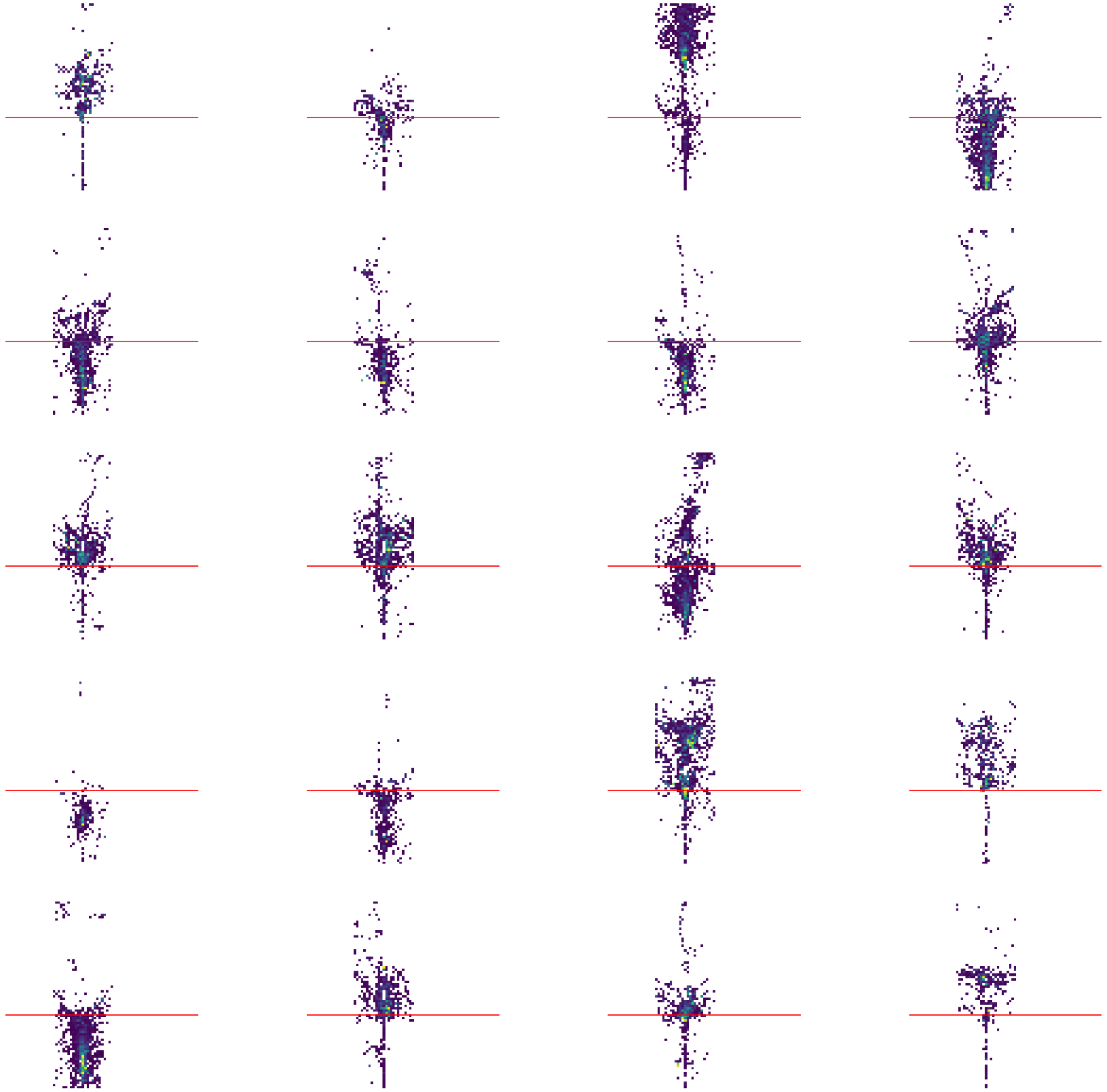
10-90 GeV π^+ showers



Geant4 Simulation



CC II with transformer

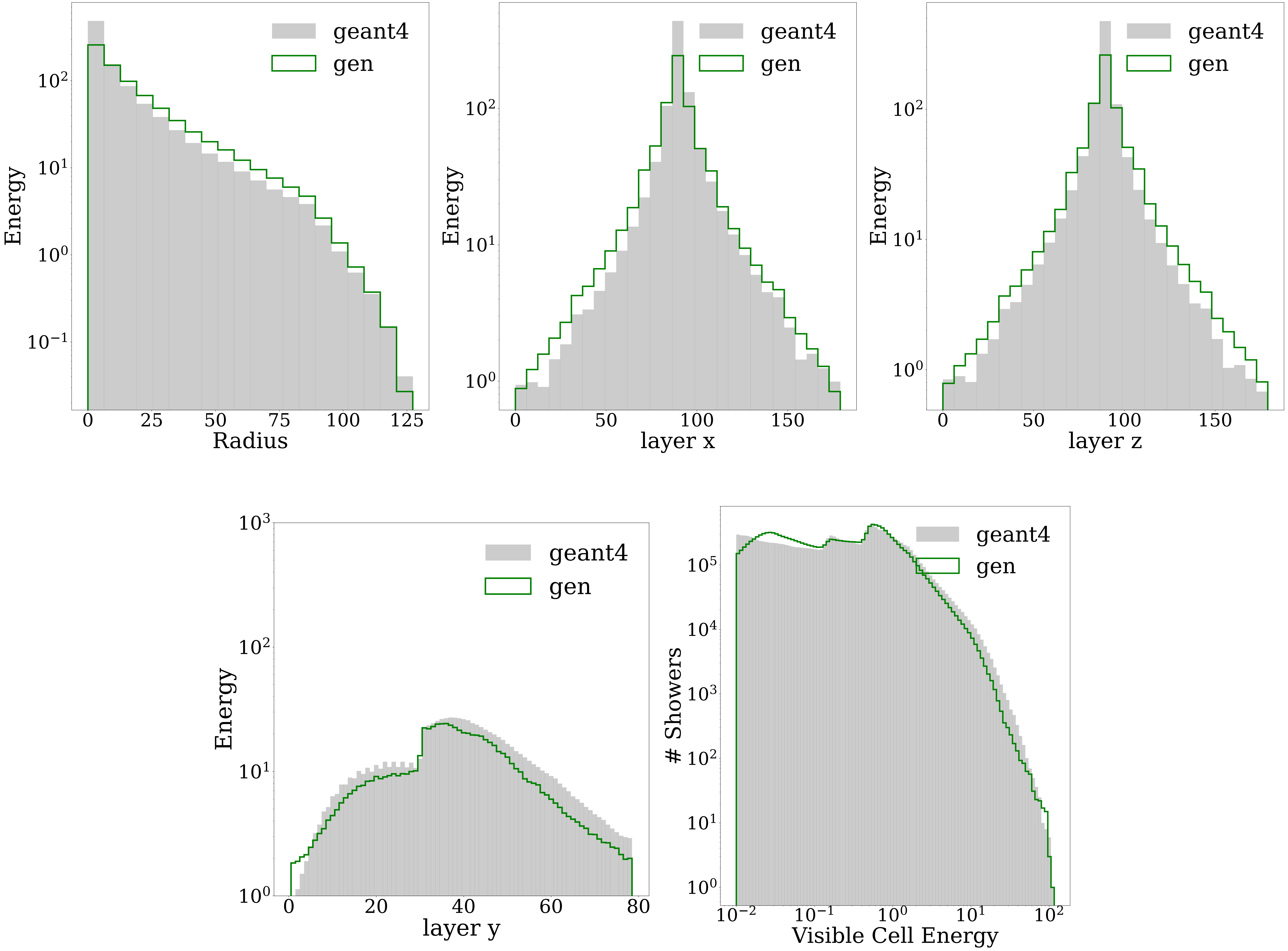


Results

10-90 GeV π^+ showers

- All evaluations with point cloud showers projected to regular cell grid (5,78,5)

- 10 000 showers



Summary

- Dealing with hadronic showers is a more complicated task than EM showers
- Clustered Geant4 steps allow for a cell-geometry-independent model
- Attention mechanism is a valid solution —> it considers interactions among points
- Ongoing work